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Analysis of 2015 Meteorological Data from the Bettis Atomic Power Laboratory

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Section 1. Synopsis

The Bettis Atomic Power Laboratory (Bettis) in West Miffin, PA is required to estimate the effects of hypothetical emissions of radiological material from its facility by the U.S. Environmental Protection Agency (EPA). An atmospheric dispersion model known as CAP88, which was developed and approved by the EPA for such purposes, is used by Bettis to meet this requirement. CAP88 calculations over a given time period are based on statistical data on the meteorological conditions for that period.

The Bettis facility has an on-site meteorological tower which takes atmospheric measurements at a frequency ideal for EPA regulatory model input. However, an independent analysis and processing of the meteorological data from the site tower is required to derive a data set appropriate for use in the CAP88 model. The National Atmospheric Release Advisory Center (NARAC) was contracted by the Bettis Atomic Power Laboratory to process the on-site meteorological data for the calendar year 2015.

The purpose of this document is to:

- Summarize the procedures used in the preparation and analysis of the 2015 meteorological data
- Document adherence of these procedures to the guidance set forth in "Meteorological Monitoring Guidance for Regulatory Modeling Applications", EPA document: EPA-454/R-99-005 (EPA-454)

Section 2. Data Background

2.1 Tower Operations

The meteorological tower at the Bettis facility is maintained by NARAC (via a subcontract with Air Resource Specialists [ARS]), in coordination with site facility personnel. The role of NARAC in tower instrument maintenance is independent from its role in this analysis.

The Bettis tower is equipped with meteorological instrumentation for measuring the following ambient parameters:

- Air temperature
- Relative humidity
- Wind speed
- Wind direction
- Precipitation (as accumulation over 15-minute periods)

The sensors on the tower are affixed at a height of 23 meters (above ground level).

The tower instruments take measurements at a frequency of a few seconds. These direct measurements are then collected and averaged over 15 minute periods by a data acquisition system (datalogger) from Campbell Scientific (http://www.campbellsci.com).

2.2 Wind Measurements

The tower is equipped with two sets of wind measuring instruments:

- A sonic wind sensor (Heated Ultrasonic Wind Sensor Model #85004) from the R.M. Young Company. (http://www.youngusa.com/Manuals/85004-90%28G%29.pdf)

- A mechanical wind sensor(Wind Monitor Model #05106-5A) using a mechanically driven propeller and wind vane from the R. M. Young Company (http://www.youngusa.com/products/7/8.html)

Both wind sensors operate simultaneously and independently, resulting in two sets of wind measurements and two sets of 15-minute averaged wind values.

While the sonic and mechanical wind instruments are co-located in order to measure the same ambient wind conditions, they operate in a markedly different manner. The sonic instrumentation, having no moving parts, responds much quicker to changes in wind flow. This quicker response time has two important consequences:

- The sonic sensor tends to produce sigma theta values that are noticeably larger than those resulting from the mechanical sensor. Sigma theta is a key parameter in the hourly averaging methodology used in this analysis and is determined from changes in the wind direction over time.

- The difference in instrument sensitivity results in a lower calm wind threshold for the sonic sensor. The calm wind threshold is the minimum ambient wind speed needed to engage a wind speed sensor (anemometer) to obtain a valid reading. The manufacturer specification for the mechanical anemometer has a reported calm wind threshold of 1.1 m/s. In contrast, the threshold for the sonic anemometer is much lower and is reported to be "virtually zero". EPA-454 provides guidance on the treatment of calm winds for mechanical instrumentation but states, "sonic anemometers are not commonly used for routine monitoring and are beyond the scope of this guide."

During the collection and averaging of the 15-minute data, the datalogger performs a series of data quality assurance tests. These tests are performed separately on the sonic and mechanical wind measurements as well as on other non-wind measurements. The tests can result in either or both of the wind sensors being flagged as suspect during a given 15-minute period.

2.3 Time Zone Convention

All times in this document are given in UTC (Universal Time Coordinates or Greenwich Mean Time). Eastern Standard Time, the standard time zone for Bettis, is 5 hours earlier than UTC.

Section 3. Data Processing Procedures

The eventual data format required by CAP88 is a joint frequency distribution of wind speed, direction, and atmospheric stability. Such a distribution shows the percentage of occurrence of all possible combinations of these parameters. Since wind speed and direction are measured directly by the tower instrumentation, the hourly averages of these two parameters suffice as input into the joint frequency distribution. However, a method is needed to determine atmospheric stability at each hour.

There are four methods recommended in EPA-454 for calculating the atmospheric stability, but only one of these methods could be used in this analysis based on the parameters measured on the site towers. This method is the commonly used "Modified Sigma Theta" (MST) method which is based on hourly averages of the:

- Wind speed
- Wind direction
- Sigma theta

3.1 Quality Assurance of 15-minute Averaged Data

In preparation for the calculation of hourly averages, a concentrated effort was made to gather the most complete, consistent and reliable data set of 15-minute averages over the 2015 calendar year.

To avoid the need to compensate for the differences between the behavior of the sonic and mechanically based wind sensors described in Section 2, 15-minute averages were gathered only from the sonic sensors. Therefore the following recovery statistics reflect sonic data recovery.

Data recovery was nearly complete for the 2015 period with over 97% of the 15-min data records retrieved: 247 missing from a total of 8760 possible (365 days x 24 hours per day x 4 averaged values per hour). Approximately 10% of the missing data could be attributed to routine tower maintenance.

A visual inspection was then done on records that had been identified by the data logger as possibly being erroneous. From these records, only one 15-min averaged entry was determined to be suspect and removed.

Hourly periods with less than four valid 15-minute averages resulted from the missing data and the removal of the single suspect wind value. Table 1 summarizes the frequency of availability of 15-minute averages for the 8760 total hourly periods in the 2015 data set.

Valid 15-min averages for each hour	Count
4	8669
3	7
2	5
1	5
0	54

Table 1 – Frequency of 15-minute averaged data sets within each hourly period over 2015

EPA-454 guidance states that any hourly period must have at least two of the possible four 15-minute averages to be considered valid. As Table 1 shows, 59 hourly periods did not meet this requirement (5 hours having only one 15-min average and 54 having no 15-min averages). All of these hourly gaps were the result of missing data.

3.2 Hourly Averaging

The computation of an hourly averaged value for each meteorological variable of interest was based on the four 15-minutes averages ending at the top of that hour. For example, an hourly average at 3:00 UTC was calculated as the average of the four 15-minute averages from 2:15, 2:30, 2:45 and 3:00 UTC.

3.2.1 Averaging Equations

The hourly averaging performed in this analysis used the following equations from EPA-454:

- Wind speed **-** Scalar wind speed equation (EPA-454 Eq.6.2.1):

$$\bar{\mathrm{u}} = \frac{1}{N}\sum_{1}^{N} u_i$$

where $\bar{\mathrm{u}}$ = average wind speed, and N = the number of 15-minute averages in each hourly period. This is an arithmetic average of the 15-minute averaged wind speeds.

- Wind Direction - Scalar mean wind direction equation (EPA-454 Eq. 6.2.4):

$$\bar{\Theta} = \frac{1}{N}\sum_{1}^{N} \mathrm{D}_i$$

$\overline{\Theta}$ = average wind direction

N = number of 15-minute averages in each hourly period

I = sample number per hour (1, 2, 3, 4)

and D_i is defined as:

For I = 1:

$D_i = \Theta_i$

For I > 1:

$D_i = D_{i-1} + \delta_i + 360$; for $\delta_i < -180$

$D_i = D_{i-1} + \delta_i$; for $\delta_i < 180$

$D_i = D_{i-1} + \delta_i - 360$; for $\delta_i > 180$

D_i is undefined for $\delta_i = 180$

where

Θ_i = 15-minute averaged wind directions

$\delta_i = \Theta_i - D_{i-1}$; for I > 1

Being a scalar average, this formula computes the average wind direction without the need for calculating the vector components of the wind directions. This averaging method is based on the assumption that the wind direction does not vary by more than 180 degrees between successive readings. There were 5 total occurrences among both sites with consecutive 15-minute averaged wind direction differing by exactly 180 degrees. In those cases, a visual inspection of the data was used to determine the appropriate average.

- Sigma theta - root-mean-square "average" (EPA-454, eq. 6.2.10)

$$\text{Hourly sigma theta} = \left[\frac{1}{N} \left\{ \sum_1^N \sigma_{\theta_i}{}^2 \right\} \right]^{½}$$

where σ_{θ_i} is the 15-minute averaged sigma theta value, and N is the number of 15-minute averages. This root-mean-square formula is recommended by EPA-454 in order to minimize the effects of wind meandering as opposed to a straight arithmetic average.

In the case of wind speed and direction, EPA-454 also allows for vector based averaging as opposed to the scalar based equations. However, that document recommends the scalar averaging approach that was used in this analysis.

3.2.2 Hourly Averaged Calm Wind Values

In order to define a calm wind threshold for this analysis, the ability of the sonic anemometer to measure wind speeds at values close to zero must be coordinated with EPA guidance on the treatment of calm winds along with the requirements of CAP88. Since the CAP88 model's defined minimum wind speed is 1 knot, an effective minimum wind speed in this analysis was taken to be 0.26 m/s (0.26 m/s = .501 knots which rounds up to 1 knot), even though the sonic can measure much lower speeds. Hourly calm wind values, i.e., wind speeds less than 1 knot, were therefore not included in the final 2014 frequency distribution for input into CAP88. The hourly averaged 2015 data set contained only one calm value.

3.3 Modified Sigma Theta (MST) Method

The MST method is a turbulence-based method of characterizing atmospheric stability through the degree of variation in wind direction (sigma theta) as measured in the raw data. The correspondence between Pasquill-Gifford (PG) atmospheric stability categories and sigma theta is given in Table 2 below:

Measured Deviation of Horizontal Wind Direction Sigma theta ranges (σ_Θ = sigma theta, in units of compass degrees)	Initial estimate of P-G Stability Category
$22.5 \leq \sigma_\Theta$	A
$17.5 \leq \sigma_\Theta < 22.5$	B
$12.5 \leq \sigma_\Theta < 17.5$	C
$7.5 \leq \sigma_\Theta < 12.5$	D
$3.8 \leq \sigma_\Theta < 7.5$	E
$\sigma_\Theta < 3.8$	F

Table 2 – PG-stability category correspondence to sigma theta data (reproduced from EPA-454: Table 6-9a).

These categories do not take into account site-specific characteristics. Therefore, adjustments of these categories were required by the MST in order to correct for both the height at which the measurements were taken and the surface roughness.

Once the necessary site-specific corrections are made to Table 2 (EPA-454: Table 6-9a), for each hourly average the MST method:

- Uses the site-specific sigma theta ranges, shown in Table 4 below, to determine an initial value of the Pasquill-Gifford (PG) stability based on the hourly averaged sigma theta values

- Uses the initial PG stability, day/night classification, and wind speed values to determine a more comprehensive value for stability using a second lookup table EPA-454: Table 6-9b

These steps are discussed in more detail in the following sub-sections.

3.3.1 Site-Specific Corrections

The MST requires an estimate of the surface roughness length for the site. Surface roughness estimates were initially made based on discussions with NARAC staff who had visited the Bettis facility. These estimates were then compared to EPA-454 (Table 6-10), which provides surface roughness estimates based on terrain characteristics, as well as the American Meteorological Society's surface roughness equation (e/30; where e = averaged height of obstacles). The final estimate of surface roughness was an approximate average of all of these sources.

The surface roughness lengths for the Bettis site was estimated to be 0.32 meters

Since this value does not match the standard surface roughness length of 0.15 meters assumed in Table 2, the following surface roughness correction factor was used (see EPA-454 Section 6.4.4):

$(Z_0/15)^{0.2}$ Z_0 = site surface roughness length (in centimeters)

The sigma theta ranges in Table 2 also assume an instrument height of 10 meters. Since the instrument height at Bettis of 23 meters differs from this standard level, a second measurement height correction factor from EPA-454, section 6.4.4 was needed:

- $(Z/10)^{\wedge}P_0$

where Z = the measurement height in meters, and P_0 is a function of stability taken from the following table:

PG Stability	A	B	C	D	E	F
P_0	-0.06	-0.15	-0.17	-0.23	-0.38	0

Table 3 – Stability-dependent exponent values for instrumentation height correction (EPA-454).

In accordance with EPA-454, the lower boundaries of each stability category in Table 2 were multiplied by the surface roughness and height corrections to produce the adjusted site-specific sigma theta ranges shown in Table 4. These adjusted sigma theta ranges were then used to determine an initial atmospheric stability class for each hour.

Bettis	Initial estimate of PG Stability Category
$25.2 \leq \sigma_\Theta$	A
$18.2 \leq \sigma_\Theta < 25.2$	B
$12.8 \leq \sigma_\Theta < 18.2$	C
$7.3 \leq \sigma_\Theta < 12.8$	D
$3.3 \leq \sigma_\Theta < 7.3$	E
$\sigma_\Theta < 3.3$	F

Table 4 - Modified version of EPA-454 Table 6-9a used in this analysis.

3.3.2 Day/Night Calculations

For the calculation of the final stability for each hour, the MST method requires that each hour be identified as occurring during the day or night. The determination of day or night periods was based on an Excel spreadsheet available from the Department of Ecology, WA. The calculations within that spreadsheet are described at the following NOAA web sites:

- "Sunrise/Sunset Calculator" (http://www.srrb.noaa.gov/highlights/sunrise/sunrise.html)
- "Solar Position Calculator" (http://www.srrb.noaa.gov/highlights/sunrise/azel.html)

Day and night values were determined from the NOAA calculators based on the solar elevation angle for each hour in the calendar year. A positive/negative solar elevation angle generated by the NOAA calculator was interpreted as a day/night value. A final adjustment was made to the calculated day hours for the periods just after sunrise and before sunset for consistency with the definition of day and night in Table 6-3 of EPA-454: "Night refers to the period from one hour before sunset to one hour after sunrise". Therefore the first and last day-time hours in a given day, based on solar elevation, were re-categorized as night-time hours.

3.3.3 Final Pasquill-Gifford Stability Estimates

Table 5 (which reproduces EPA-454: Table 6-9b) was used to determine the final stability values from the initial PG classification, the day/night designation, and the wind speed.

	Initial Estimate of PG Stability	wind speed	Final Estimate of PG Stability
Daytime	A	$u < 3$	A
	A	$3 \leq u < 4$	B
	A	$4 \leq u < 6$	C
	A	$6 \leq u$	D
	B	$u < 4$	B
	B	$4 \leq u < 6$	C
	B	$6 \leq u$	D
	C	$u < 6$	C
	C	$6 \leq u$	D
	D, E, or F	any	D
Nighttime	A	$u < 2.9$	F
	A	$2.9 \leq u < 3.6$	E
	A	$3.6 \leq u$	D
	B	$u < 2.4$	F
	B	$2.4 \leq u < 3.0$	E
	B	$3.0 \leq u$	D
	C	$u < 2.4$	E
	C	$2.4 \leq u$	D
	D	any	D
	E	$u < 5$	E
	E	$5 \leq u$	D
	F	$u < 3$	F
	F	$3 \leq u < 5$	E
	F	$5 \leq u$	D

Table 5 – Final stability values for Modified Sigma Theta method incorporating day/night and wind speed values (EPA-454: Table 6-9b).

3.4 CAP88 Input

The deliverable product required from this analysis was a summary of the hourly stabilities and wind values for use in running the CAP88 program. The standard CAP88 input format for meteorological data is an ASCII "Wind File" (WND). The WND file was generated via a CAP88-provided utility that uses as input a joint frequency table of stability and winds in "Stability Array file" (STAR) format.

The LLNL analysis created an appropriate STAR file based on the 2015 data from the Bettis tower. To create the STAR file, the hourly-averaged wind data was processed as follows:

- Each hourly wind direction was converted to its corresponding sector: e.g. NNE or North/Northeast
- Wind speed units were converted from m/s to knots and rounded to whole integers

A LLNL-developed program was then used to process the hourly wind and corresponding Pasquill-Gifford stability categories into the appropriate joint frequency category and count those values accordingly.

Two WND files were created: one being the abovementioned WND file as generated with CAP88 version 3.0, and the second WND file representing a CAP88 version 4.0.1.17 compatible format allowing for station information to be included. An end-user has the option of using either WND file in the newer version of CAP88. The newer, CAP88 version 4.0.1.17, WND file was generated using a migration utility provided by this updated version of CAP88 and provides site specific information.

Section 4. Summary

This document outlines the steps in analyzing and processing meteorological data from the Bettis Atomic Power Laboratory into a format that is compatible with the steady state dispersion model CAP88. This process is based on guidance from the EPA regarding the preparation of meteorological data for use in regulatory dispersion models. The analysis steps outlined in this document can be easily adapted to process data sets covering time periods other than one year. The procedures will need to be reviewed should the guidance in EPA-454 be updated or revised.

References

United States Environmental Protection Agency, Office of Air Quality Planning and Standards, Meteorological Monitoring Guidance for Regulatory Modeling Applications (EPA-454/R-99-005), February 2000.

Auspices

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